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ADVANCED DISTRIBUTED SIMULATION TECHNOLOGY ADVANCED ROTARY WING AIRCRAFT

STUDY COMPARING APPROACHES TO MODELING THE ARWA MAIN ROTOR

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1. Scope.

The Advanced Distributed Simulation Technology (ADST) Advanced rotary Wing Aircraft (ARWA) Study Comparing Approaches To Modeling The ARWA Main Rotor is presented in this document. This report provides details of technical approaches for both a blade element model (BEM) and a rotor disk model (RDM) to simulate the flying qualities of the ARWA Simulator System (SS). A background of aero-modeling techniques and a discussion of the technical and cost merits for both approaches is provided.

1.1. Identification.

The ADST ARWA Study Comparing Approaches To Modeling The ARWA Main Rotor is submitted under Contract No. N61339-91-D-0001, Delivery Order Number 0048. Loral Technical reference number for this document is ADST/TR 94-003280.

1.2. Overview.

The ADST ARWA SS provides a rapidly reconfigurable, DIS compatible, VV&A "-ed" aviation test bed capability at the Ft. Rucker, Alabama, Aviation Test Bed (AVTB) facility to support combat developments, training developments, materiel developments, and concepts evaluation on the virtual combined arms battlefield. The ARWA SS has as its technical objectives efficiency, reuse based, high quality software, specific functionality, and a V&V "-able" product.

The ARWA simulator device presents the crew with an environment that represents the tactical look and feel of the real aircraft with all features required to perform the mission functions associated with the tactics development and training intent of the ARWA device. The extent to which the ARWA simulator device replicates the tactical configuration for the aircraft is determined by a Task and Skills analysis, and a subsequent Selective Fidelity analysis. Initially, the ARWA simulator devices replicate the RAH-66 Comanche Recon Aircraft and the AH-64D Longbow Apache Attack Aircraft.

Supporting the "move-and-shoot" mission requires a flight dynamics model of sufficient fidelity to move and position the ownship platform, and to provide the pilot with sufficient position, attitude and movement cues to support the mission tasks. The aircraft specific kits are baselined with a rotor disk model provided by the airframe manufacturers and modified for a real-time system. The open architecture of the ARWA SS supports the replacement of the aeromodel with a higher fidelity model as required. Factors which impact a decision to integrate a higher fidelity model include fidelity requirements, software development/procurement cost, hardware cost, and maintainability. This report is provided as a task of the Statement of Work (SOW) for Acquisition of the Advanced Rotary Wing Aircraft Simulator System, Version 3.0, dated 11 June 1993.

2. Referenced documents.

Statement of Work for Acquisition of the Advanced Rotary Wing Aircraft (ARWA) Simulator System, Version 3.0, dated 11 June 1993

3. Aeromodeling background.

To provide effective tactical mission support, the aerodynamic models, must accurately describe six-degree-of-freedom flight.

The typical six-degree-of-freedom dynamics model is structured as follows. The force and moment loads acting on the airframe are computed locally at the surfaces they are affecting. These loads are then resolved to the airframe center of gravity and summed according to this common reference point. Then the Newtonian equations of motion for both angular and translational motions are solved according to the force and moment sums and inertial characteristics of the airframe. The Newtonian equations output the translational and rotational accelerations about all six-degrees-of-freedom. Numerical integrations are then performed to derive the full aircraft state: rates, velocities, attitude, and position.

The flexibility factor in flight modeling which accounts for the possible variation in the way models are constructed is introduced at the point where the force and moment loads are derived. These derivations can be simple or complex and can result in various levels of physical fidelity.

The necessity for a full six-degree-of-freedom flight model holds especially for the ownship simulation and to a lesser extent for the players. The handling qualities nuances perceived by the ownship pilot cannot be perceived when observing a player on a visual system projection. Usually, there is only one ownship model in a simulation system, but there may be many player models -- serving as threats, friendlies, or merely traffic to be avoided. Flight models are built for the ownship and players with different levels of complexity and fidelity to meet the handling and performance requirements.

3.1 Rotary Wing Aircraft.

Because helicopter flight is more complex and not as well understood as fixed-wing flight, helicopter flight models tend to be larger, more complex, and less accurate than fixed-wing flight models.

Some of the problem stems from the main rotor. The aerodynamic forces on the helicopter depend not only on vehicular airspeed and angle of attack, but also on the main rotor blade section velocity and angle of attack. These blade section variables depend on the rotor rotational speed, vehicular attitude, blade flapping, blade coning, blade in-plane motion, and cyclic and collective pitch. Additionally, the main rotor downwash produces interference effects on the other parts of the airframe. Some of the problem stems from the enhanced flight regime possible to a helicopter -- hover, vertical flight, sideward and rearward flight.

Four main types of helicopter flight models have emerged. They differ in their approach to modeling the helicopter main rotor. They are listed below in order of increasing complexity and increasing potential fidelity.

1) Perturbation Models
2) Rotor Disk Models
   a. Rigid Disk Models
   b. Rotor Map Models
3) Blade Element Models

3.1.1 Perturbation Models.

Perturbation models represent the simplest approach to the simulation of real-time helicopter flight. In the tradeoff between fidelity and complexity, these models fall on the low fidelity-low complexity end of the spectrum.

Perturbation models forego a separate main rotor representation by lumping rotor effects into a set of total aircraft dynamic characteristics (time derivatives for each of the aircraft's six-degree-of-freedom) defined over a set of pre-determined trim points.

When the current flight conditions (attitude, control inputs, etc.) approximate one of these trim points, simulation fidelity can be quite satisfactory. When flight conditions differ from the trim points, however, fidelity is usually poor. Dynamic fidelity also suffers in these types of models. When transitioning from one trim point to another, the model flight response is interpolated along the straight line derivative paths defined by the trim table. This interpolated response poorly simulates the complex behavior of the helicopter aircraft in these types of maneuvers.

3.1.2 Rotor Disk Models.

Rotor disk models consist of two subclasses of models: rigid disk models and rotor map models.

3.1.2.1 Rigid Disk Models.

A rigid disk model is based on the idealization of the main rotor as a rigid uniform disk *articulated about the rotor hub.* These models represent a step up in complexity from the perturbation models described in the previous section and tend to be more analytical in nature than the perturbation models. Hence, they provide more insight into and understanding of their performance. Yet they cannot be as easily "tuned" to yield a close fit to a desired level of performance.

The basic structure which fits all the diverse types of rigid disk models can be described as follows. The rotor disk is assumed to be both rigid and solid. Hence, there is no blade simulation and consequently, blade dynamic behavior such as coning, flapping, and in-plane lead-lag motion is ignored. The rigid and uniform rotor disk is assumed to induce a uniform inflow velocity over its surface. This assumed inflow can be used to derive the local angle of attack and local velocity at each radial and azimuth station on the disk. Disk loads are then derived by analytically integrating the local loads across the disk surface. These integrations produce analytical expressions describing rotor thrust, hub drag force, hub side force and torque as functions of disk attitude and collective pitch. Additionally, most rigid disk models use an iterative technique to balance thrust and inflow.

3.1.2.2 Rotor Map Models.

The hallmark of a rotor map model is the dependence of the rotor simulation on a stored database. The rotor simulation is more comprehensive than that for the rigid rotor. The stored database is composed of steady state coefficient values of rotor thrust, torque, drag, sideforce, and longitudinal and lateral flapping motion over the entire flight regime. Inflow ratio, advance ratio, and collective pitch usually serve as the independent variable indices for the data table lookups. Other rotor characteristics are derived from closed form analytical equations which depend on the data from the lookup tables. Additionally, an iteration method is commonly employed to balance inflow and thrust.

The rotor disc map approach effectively orients the rotor resultant force vector along a known direction prescribed by the control inputs of the pilot. This reference direction is the control axis of the rotor. More importantly, the rotor disc map model makes use of the fact that - at a particular Mach number, air density, and rotor speed - the steady state of a rotor is uniquely defined by three independent rotor variables: the resultant free stream velocity at the rotor, V; the rotor angle of attack, α_R; and the rotor collective blade pitch angle, θ_O. Given a particular set of values of the rotor variables (V, α_R, θ_O), there can be one and only one rotor state, regardless of the values of any other variables associated with the rotor. The rotor state includes such parameters as forces, torque, coning and flapping angles, and induced flow characteristics. This governing concept (that the operating of any rotor can be completely defined by the definition of these three independent variables of the rotor) has been accepted by rotor aerodynamicists for many years.

The rotor resultant free stream velocity V is the effective airspeed experienced at the rotor due to the gross motion of airframe and the movement of the rotor relative to the aircraft center of gravity. The rotor angle of attack is defined as the angle between V and a perpendicular to the rotor control axis. The control axis is defined as the axis about which the pitch of the blades do not vary with azimuth position; that is, the control axis is the axis of no feathcring. In a control axis system, the control axis is taken as the z-direction. A rigorous definition of the control x-axis direction places it in the plane formed by the control z-axis and thc nct relative wind vector (V), and perpendicular to the z-axis. Thc control y-axis completes the orthogonal triad.

The collective blade pitch angle θ_O is the incidence of the blade with respect to a perpendicular to the control axis. This angle may be conveniently referenced to any radial station of the blade such as the hub, the center of rotation, or the 75 per cent radius station.

Rather than using the rotor independent variables (V, α_R, θ_O) exclusively, it is sometimes convenient to express the rotor state in terms of altered variables. These variables essentially normalize the independent variables by the rotor tip speed, ΩR, and thus remove rotor speed as an independent variable. The most common form of the normalized independent variables is (μ, λ, θ_O) where

$$\mu = \frac{V \cos \alpha_R}{\Omega R}$$

$$\lambda = \frac{V \sin \alpha_R}{\Omega R} - \frac{v_i}{\Omega R}$$

μ is called the tip-speed ratio, while λ is called the inflow ratio (where v_i represents the rotor induced velocity, which itself is unique for a given rotor state). Other forms of the modified rotor independent variables that may be used are μ_O and λ_O defined as:

$$\mu_O = \frac{V}{\Omega R}$$

$$\lambda_O = \frac{V \sin \alpha_R}{\Omega R}$$

The unique set of (V, α_R, θ_O) define a unique set of (μ, λ, θ_O), so these variables also act as true independent variables, defining one and only one corresponding rotor state.

The heart of the rotor disk map model is based on the concept that the characteristics of the rotor state can have one and only one set of values for a given set of values of the independent variables of the rotor. On this premise, sets of key rotor variables needed in a rotor dynamic model for helicopter simulation may be calculated beforehand at various combinations of the rotor independent variables; these values may then be stored as data maps as functions of (μ, λ, θ_O) within the simulator program. During real-time operation of the simulator, it is necessary to calculate only the rotor independent variables, and then retrieve the needed rotor parameters from the stored rotor data tables.

The unique definition of the rotor condition at a particular (μ, λ, θ_O) state carries with it no simplifying assumptions or small value limitations. This concept is based on the rotor being in a steady condition. Rotor theory shows that in disturbed motion, the rotor responds as if the instantaneous values were steady. Therefore, quasi-steady treatment of rotor behavior (in which the rotor response is calculated as if the continuously changing motion were a series of instantaneous steady states) is justified.

The forces, torque, and flapping angles as a function of (μ, λ, θ_O) are generated or gathered off-line, prior to building the rotor disc map model. Thus the rotor solution is not solved by the on-line (real-time) helicopter simulation; the simulation problem simply solves the rotor state (μ, λ, θ_O) and the only possible solution of the rotor state is then fetched from the stored table of values.

Once the rotor forces, moments, and torque have been resolved within an appropriate body axis system, they are summed with all the other forces and moments acting on the helicopter to yield the accelerations of the aircraft. The aircraft accelerations are integrated to yield aircraft velocities. The angular velocities are integrated to find the aircraft attitude. The velocity at the rotor can then be determined, as can the orientation of the control axis (according to pilot inputs of A_{1s} and B_{1s}. Thus μ and λ can be solved; θ_O is a known pilot input. Thus the cycle is ready for solution again for the next program duty cycle.

3.1.3 Blade Element Models.

A blade element model calculates the aerodynamic and inertial loads on each element or two-dimensional section of the rotor blade as it moves around the hub. Total rotor performance is computed by numerically integrating the load contributions of each blade element along the blade span to derive the blade loads. The blade loads are then summed to arrive at total rotor performance. A blade element model represents the most analytical and comprehensive approach to rotor simulation since it treats the detailed inflow and loading of each blade in the rotor.

A blade element approach is used to model each main rotor blade. Total rotor forces and moments are produced by summations of forces from each blade, which are determined from aerodynamic, inertial, and gravitational forces. Aerodynamic forces are computed from angle of attack and dynamic pressure acting on each blade segment based on the orthogonal velocity components. These components are determined as functions of blade azimuth, lag and flap angles, local velocity of the blade segment, and local downwash. Downwash is approximated to have a first harmonic distribution as a function of wake skew angle. Blade inertial and gravitational forces are computed from blade rotational velocity, lagging and flapping velocities and accelerations, and blade position. The

summations of forces act on the airframe at the blade hinge and lag damper locations. Rotor moments result from blade hinge and lag damper offsets from the main rotor shaft.

Real-time simulation of a blade-element rotor requires that time steps be as small as possible. Modeling of high bandwidth dynamics also requires small time steps. In addition, delays from cockpit input to visual- and motion-systems output must be minimized. The outputs from each program module must be computed from one pass through the module. Internal iteration is used only when it is unavoidable, because a constant time step must be based on the maximum number of iterations needed. For each program pass, forces and moments from each component are computed and summed, from which the net translational and angular accelerations acting on the airframe are determined. The resulting body-fixed velocities and positions are used sequentially in the succeeding intervals to emulate a continuum solution to the total system.

The time-step size has a large effect on the output from the blade-element rotor program. The rotor model contains its own integration algorithms, tuned to give correct flapping and lagging positions and velocities in the rotating reference frame of the rotor hub.

The sequential nature of the "one-pass requirement" leads to algebraic loops in digital simulation. Algebraic loops are a result of sequential computation of interdependent parameters and must be prevented wherever possible through careful designing of code sequence and hierarchy. A discrete model must necessarily provide a value for a variable at the end of a time interval based on both its previous value and the values of parameters upon which it is dependent at the beginning of the interval. In the real world, the variable is dependent on the values of other parameters at the same instant in time. The occurrence of an algebraic loop can result in significant differences in phase compared to the continuous system and the dynamic stability of the system can be affected. The real-time program has been sequenced, integration algorithms have been chosen, and the time-index corrections have been used to minimize these effects.

4. ARWA SS Approach.

The ModSIM-based ARWA SS architecture does not dictate the type of implementation to be used for a software model nor the host hardware. The architecture does require an adherence to a well defined and structured interface between segments and intra-segment. This architecture approach supports replacement of individual segments, CSCIs, CSCs, and CSUs. A rotor model is implemented as part of the flight dynamics segment, and can be modified or replaced as required by performance and mission requirements. While an RDM was selected as the baseline approach for the rotor model, a blade element model can be integrated as a replacement for the RDM if higher fidelity is required of the flight dynamics model.

4.1 Baseline Approach Using Rotor Disk Model.

A rotor disk model approach was selected as the baseline approach for the ARWA SS and the initial aircraft implementations of the RAH-66 Comanche and AH-64D Longbow Apache. Task and Skills Analysis (TSA) and Selective Fidelity Analysis (SFA) studies were completed for each of the ARWA SS selected aircraft by subject matter experts at Loral's subcontractor, Illusion Engineering, Incorporated (IEI). In developing the TSA/SFA studies, the SMEs worked and coordinated closely with the airframe manufacturers and with the U.S. Army TRADOC System Managers (TSM) for Comanche and Longbow Apache, and users. Based on the purpose and function of the ARWA SS, performance and mission support requirements, input from IEI, program schedule, and

implementation cost issues for hardware and software, the RDM was selected as sufficient to support development of war fighting skills.

4.1.1 AH-64D Longbow Apache Rotor Disk Model.

McDonnell Douglas Helicopter Systems, Mesa, AZ, the original equipment manufacturer, was selected to supply the flight dynamics model for the AH-64D Longbow Apache simulation kit. These models have been extensively tested and tuned to replicate the performance and handling characteristics of the AH-64D Longbow Apache rotary wing aircraft. McDonnell Douglas Helicopter Systems, Mesa, AZ, is the developer and manufacturer of the AH-64D Longbow Apache rotary wing aircraft.

The main rotor model used as the baseline for the ARWA SS AH-64D Longbow Apache rotary wing aircraft is provided as part of the aeromodel software kit. The model is derived from the Fly Real Time (FLYRT) model developed and currently used by the engineering group in the McDonnell Douglas Helicopter Systems engineering simulator. The main rotor is a table-look-up procedure of a rotor map generated off-line. The rotor map consists of a table of a six-state vector (rotor thrust, shaft torque, two in-plane forces, and longitudinal and lateral cyclic flapping angles) as a function of three performance parameters: collective pitch at 3/4 radius, inflow ratio and axial flow ratio. For a given value of the performance parameters, the table-look-up procedure returns a six-state vector. The rotor map is generated by a dedicated off-line program called Generic Rotor (GENRO). The rotor map table has approximately 9000 entries. By virtue of the procedure to generate the rotor state, the rotor map is a quasi-static model and therefore provisions are made to simulate internal dynamics and the induced flow field.

FLYRT has been used extensively in a manned simulation mode for investigation of helicopter flying qualities. It has been used for studying handling qualities and flight control law development during the design phase. FLYRT has been validated against flight test data using both open loop step control inputs and emulating specific maneuvers. It has been used to model unconventional configurations including the No Tail Rotor (NOTAR) program and to simulate extreme maneuvers, including loop and roll maneuvers on the AH-64D.

The AH-64D RDM exists, runs in real-time on a single Motorola processor within a VME chassis, and requires minimal integration with the system. It is compatible with the government furnished equipment (GFE), highly traceable for V&V purposes and meets the requirements to support the development of war fighting skills in the ARWA SS.

4.1.2 RAH-66 Comanche Rotor Disk Model.

Boeing Defense & Space Group, Huntsville, AL, was selected to supply the flight dynamics model for the RAH-66 Comanche simulation kit. Boeing Defense & Space Group will utilize models from Boeing Helicopter Company, Philadelphia, PA. Although the Comanche production aircraft does not exist, these models have been extensively tested and tuned to replicate the expected performance and handling characteristics of the RAH-66 Comanche rotary wing aircraft. Data for these models is based on collected data from prototype rotor systems, and engineering simulation development. Boeing Helicopter Company is a member of the FirstTeam, and a joint partner in the development and manufacturer of the prototype RAH-66 Comanche rotary wing aircraft.

The main rotor model used as the baseline for the ARWA SS RAH-66 Comanche rotary wing aircraft is provided as part of the aeromodel software kit. The model is derived from the model developed and currently used by the engineering group at Boeing Helicopter

Company, Philadelphia, PA. Like the Longbow Apache main rotor model, the Comanche main rotor is modeled as a quasi-static disk, simulating the rotor as a whole disk rather than a set of blades including the dynamic effect of longitudinal and lateral rotor blade flapping. The main rotor mathematical model is based on the Wheatley-Bailey technique which reduces the complex differential equations of motion of the blade element technique to rotor map data tables. These data tables are used to compute the rotor thrust, drag, sideforce, torque and flapping angles as functions of the disk velocity components, advance ratio, inflow ratio and collective pitch of the rotor.

The Comanche aeromodel has been used to develop the design of the aircraft, aircraft systems, flight control laws, and pilot to vehicle interfaces during the prototype development phase. The RAH-66 RDM exists, runs in real-time on a single processor, and requires minimal integration with the system. It is compatible with the government furnished equipment, traceable for V&V purposes and meets the requirements to support the development of war fighting skills in the ARWA SS.

4.2 Upgrade Approach Using Blade Element Model.

If a higher fidelity rotor model is required, an upgrade to a blade element model approach can be made by replacing the RDM. We have several solutions to supplying a BEM. Each solution involves added software and hardware implementation costs. The following paragraphs discuss the advantages and disadvantages of these solutions to implementing a BEM. Section 5. Advantages and Disadvantages of RDM versus BEM discusses the merits of the RDM versus the BEM approaches.

4.2.1 BEMs from the airframe manufacturers.

Both McDonnell Douglas Helicopter Systems and Boeing Helicopter Company have working BEM models. Each company would supply a BEM for their specific airframe. The advantages to this solution is the minimum integration risk with respect to performance, V&V traceability, and system compatibility, i.e., with the existing propulsion and flight controls segments. Each model replicates the performance and handling of a particular airframe to a very high degree. The disadvantage lies with the separate and specific software models for each aircraft. Adding other airframes may require new models replicating thc specific airframe.

4.2.2 Generic BEM.

Another solution to the BEM approach is to use a generic model. This type of model must be flexible using changeable parameters and reconfigurable structure for modeling a variety of physical configurations, i.e., teetering, hingeless, etc. The ideal generic model would let the user select the RDM approach and data or the BEM and data at the time of building the executable. Loral Defense Systems - Akron has worked with developing such a model. It still has the same advantages and disadvantages.

A generic model would have commonality of software and structure. The advantage of a generic model lies in the use of a single model modifiable for individual aircraft rotor systems. However, there are several disadvantages. Generic models are highly desirable, but have remained somewhat elusive. The availability of a high fidelity model is limited. They are more costly upfront, and usually with limited rights. Tradeoffs are made to achieve model reusability. Tuning a generic model is usually more time consuming and the V&V effort increases.

5. Advantages and Disadvantages of RDM versus BEM.

The two major tradeoffs inherent in flight modeling are: (1) model fidelity versus increased computer processing resources (time and memory); (2) and (sometimes), model fidelity versus increased empiricism and attendant decreased physical understanding.

The first of these tradeoffs has already been discussed. Clearly for player models, we can accept lower fidelity and thus lessen the system's computational burden. BEMs are very computational intensive. This equates to higher equipment costs. In addition, the higher fidelity results in higher development costs, longer development and implementation schedules, and higher maintenance costs. If the fidelity increase is not warranted by the performance requirements, the higher equipment costs are not justified. Our evaluation of the purpose of the ARWA SS and inputs from our SMEs do not support the added costs of the BEM approach.

The second tradeoff is an engineering issue. Designers prefer to have a physical understanding of the model. Hence, the model should have an analytical character. It should be based on equations and algorithms which originate from physical principles. It should try to describe all relevant physical phenomena. Such a model serves well as an engineering aid. With such a model, it is instructive to vary parameters and assumptions and compare the new results with the old. Unfortunately, there is no guarantee that such a model will fly like any particular aircraft. To achieve this kind of fidelity, it is sometimes more effective to specify flight performance on the particular aircraft to be simulated and then build the model from this performance database. The model then takes on the form of data table lookups and interpolations rather than analytical expressions and algorithms. It becomes empirical rather than analytical.

For high performance manuevers and flight within areas outside of the normal flight envelope, a BEM may be needed, specifically to provide realistic performance response for coupled systems. Generating rotor maps for all possibilities would be prohibitive, and transitions from one map to another may result in some discontinuities. These discontinuities would not be present in a BEM.

For training applications, models typically represent existing aircraft and their usage is limited to non-engineering purposes. Therefore, empirical models, giving a good fit to the flight data yet little intuition to the underlying principles, are acceptable in this realm.

5.1 Perturbation Models.

The advantage of perturbation models lies in their simplicity. They are easily developed and require few computer resources to run in real-time.

The disadvantage of perturbation models is that they do not have a high level of fidelity to replicate performance and handling qualities throughout the flight envelop.

5.2 Rigid Disk Models.

The advantage of rigid disk models lies in their relative computational simplicity. They require only four analytical functions to describe the rotor disk loads. For many applications, the simplifying assumptions used to derive the models (rigid disk, no blade motion) are accurate enough to yield acceptable model performance.

The drawback of rigid disk models lies in their inability to be adjusted or "tuned" to achieve static performance criteria. Also there is no way to estimate the number of iterative passes required to achieve convergence in the thrust-inflow balance algorithm.

5.3 Rotor Map Models.

The advantage of the rotor map models lies in the ability to adjust the coefficient data in the lookup tables to achieve compliance with static performance data gathered from flight test or elsewhere. Also, this model has an analytical character in the simulation of dynamic effects and so lends itself to a fuller understanding of its resulting performance.

The disadvantages of the rotor map models are threefold. First, the coefficient tables must be initially generated by a blade element model running in non-real time. Until the completion of the process of coefficient "tuning" the model performance can be no better than that of the source blade element model. Second, this kind of model requires more computational complexity because of the number of coordinate transformations and table lookups required for implementation. Third, the number of iterations required to balance inflow and thrust varies greatly over the flight regime. This variation poses problems for real-time operation.

The rotor map main rotor model, while computationally very efficient, has several shortcomings. It is limited to only moderate variations of rotor RPM and temperature at which the rotor map was generated. A rotor map generated at 100% rotor RPM is used for most applications, it is restricted to maneuvers which involve a maximum of +/- 5% excursions in the rotor RPM. Large changes in temperature need different rotor maps to correctly account for stall and Mach number effects on the rotor blade. The transient solutions in the rotor map model, which are computed from closed form linear solutions and superimposed on the quasi-static solution, are valid only for maneuvers involving nominal body angular rates and for flight conditions where the blade section aerodynamics are in the linear range.

5.3.1 Fast and computationally undemanding.

The rotor disc map model is very fast since the bulk of the rotor solution has been done off-line. The rotor disc map solution is easily accommodated within a simulation program requiring 32 solutions per second. The memory requirements of the rotor disc map program itself is very small. The memory requirements of the stored rotor data and associated interpolation routines is reasonable. Approximately 5,000-10,000 data points are stored for a complete set of rotor maps.

5.3.2 Choice of selection of best available rotor data.

Since the rotor data are generated external to the actual real-time simulation program, the source of these data, and the degree of accuracy used to generate them, is the choice of the user. Data may be generated by analytic programs run and developed by the simulator manufacturer, the airframe manufacturer, or from some universally available program. The degree of accuracy these programs use to solve the rotor state is unaffected by the real-time requirements of the simulator. If available, rotor wind tunnel, whirl stand, or flight test data may be used directly as the source of rotor disc map data, or may be used to correlate and modify analytically-generated data. No compromising simplifications need be made in any of the techniques for off-line generation of the rotor data used in conjunction with the rotor disc map model. Also, mixes of data sources are possible if better accuracy for the resultant data set is envisioned.

5.3.3 Uncomplicated independent variables.

The independent variables (μ, λ, θ_O) are based on the set (V, α_R, θ_O). Given accurate rotor data, any inaccuracy in rotor contributions to the trim and response characteristics of the helicopter have to be based on the calculated values of V and α_R. θ_O is in itself a known pilot input. The rotor angle of attack is also based on known pilot inputs A_{1s} and B_{1s}. The rotor velocity is a relatively straight-forward solution of aircraft kinematics. Therefore, given the acceptance of the rotor map data supplied to the rotor disc map model, any inaccuracy in solution can be traced to the calculation of the rotor independent variables or else is due to some contributor other than the rotor (such as the fuselage aerodynamics). This is an important quality when correlating a simulator with design acceptance criteria data, and correcting the simulator as required.

5.3.4 Accessibility/capability for modification.

Another benefit that the rotor disc map model provides when correlating and correcting the simulator in order to meet performance requirements is its accessibility to modification. If the rotor data loaded into the rotor disc map model proves to be inadequate in accuracy in certain portions of the flight envelope, these data may be modified with a reasonable amount of effort in order to get the simulator to better meet actual helicopter test data in these flight regimes. The form of the rotor data maps is explicit in hey parameters such as thrust and torque which are so important in their effect on the overall trim or response of the helicopter. The effects of modifications of these data maps are directly and immediately evident in the resulting simulation problem; such changes may even be made and evaluated on-line as the simulated helicopter is flying.

5.3.5 Flexibility within the simulation model.

The rotor disc map technique allows minor and moderate changes in the form of the rotor model to be made with little effort. such changes may be required because the best available rotor data is in a form that is somewhat different from conventional form. An example would be airframe manufacturer-generated rotor data as a function of (μ_O, λ, θ_O) rather than (μ, λ, θ_O). Also, the form in which rotor induced velocity at the tail is presented can vary, with accommodations easily made within the rotor disc map model. This characteristic of the rotor disc map model is useful because off-the-shelf rotor data available from the airframe manufacturer can be used by making minor changes to the rotor disc map model, rather than demanding the more costly and time-consuming route of having the airframe manufacturer re-generate the rotor data according to the particulars of the simulator manufacturer.

5.3.6 Simulation of various rotor types.

With a minimum amount of effort, the rotor disc map model can be modified to simulate virtually every type of helicopter rotor (see-saw, articulated, hingeless, and rigid), and yield a high level of model accuracy for each type.

5.4 Blade Element Models.

Blade element modeling has been widely considered as the superior technical approach to rotor simulation. Its strength lies in its high degree of model analyticity coupled with a high degree of dynamic simulation fidelity. This high fidelity stems from its ability to account for both the non-uniform nature of inflow across the rotor disk and the transient

conditions that frequently occur in rotary wing flight. A blade element model can allow for all possible degrees of freedom of blade motion, and hence can simulate handling qualities nuances lost in other types of models.

On the debit side, however, a blade element approach levies the heaviest computational load of all the models so far considered. Real-time blade element simulation is done on computers which perform at the high end of the spectrum. Also, a blade element model can fail to match static rotor performance data because of its use of a two-dimensional blade element simulation operating in a three dimensional environment. And since the model does not draw upon a stored database of acceptable rotor performance data, the model cannot be easily "tuned" to achieve the desired static performance.

Maneuvers involving high angular rates, roll-reversal for example, require comprehensive blade element rotor model to account for the transient effects and to represent the non-linear blade aerodynamics. A blade element rotor model also provides the means to include aerodynamic refinements such as dynamic inflow, dynamics stall, radial drag, tip Mach-relief effects, and wake effects. It provides the necessary rotor degrees-of freedom to dynamically couple the main rotor with the body and drive train. It can also more accurately predict blade loads and control loads. A blade element rotor model provides an overall comprehensive rotor modeling capability.

5.5 BEM Implementation Impact.

The advantages of using a blade element model in the ARWA SS simulation in lieu of the proposed rotor map model may not be realized by the pilot at the controls with the current design approach. Simply replacing one rotor model with one of greater fidelity and accuracy does not necessarily produce a like transfer to the man-in-the-loop. The resultant benefit to the pilot at the controls is dependent on the sophistication of the total simulation. There are three major areas in the ARWA SS simulation that could dilute the performance gains of a blade element model. These are the propulsion, flight controls, and environment segments.

For instance, the baseline propulsion model to be implemented for the RAH-66 Comanche application is not a true T800 simulation, but merely a generic turbine model which provides the flight dynamics (power train) with torque values within the T800 specification limits. This will provide the flight station/pilot with indications of small rpm perturbations or rotor decay commensurate with power applications based upon a first order filter.

The flight controls simulation for the RAH-66 Comanche application is planned to be a combination of simulation software currently in use in the Boeing Helicopters engineering laboratory and newly developed code to simulate capabilities of the RAH-66 not yet developed. The approach for developing the new code is to provide a simulation that supports the minimum capabilities as defined in the Selective Fidelity Analysis and provide those to the pilot as described in the PVIMS Block 2. The simulation of systems such as Coupled Navigation (CNAV) or Integrated Fire and Flight Control (IFFC) will be driven by functional requirements rather than design criteria data since none are available. Therefore, certain subtle, inherent peculiarities of the flight control system may not be perceived by the pilot. Additionally, a low cost, off-the-shelf control loading system will be used in the RAH-66 ARWA simulator. This may further mask small flight control characteristics because the control law algorithms currently developed and in use are tightly coupled to the actual aircraft flight control hardware and software still in development. Existing Flight Controls control laws were developed using a rotor map model. Discontinuities may result if these control laws are used with the blade element model.

The ARWA SS environment segment does not support the fidelity necessary for a blade element model to accurately simulate hovering flight to the degree that would make it significantly superior to other models. For example, the blade element model being considered for the RAH-66 ARWA simulation samples 10 points along each blade every 8.5 degrees and runs 180 Hz. This allows the rotor blades/system to react to small variations in the terrain height and surface (i.e., sloping, flat, smooth, tall grass, etc.) during hovering flight. The environment segment will only provide the flight dynamics segment with a single terrain height based on the database height from the center of gravity (cg) of the entity (helicopter) and will always be flat. Therefore, the data required by the model to accurately simulate hovering flight is not available.

Based on the limitations of the current RAH-66 ARWA baseline, it is doubtful that any measurable performance enhancement will be gained by simple "dropping in" a high fidelity blade element rotor model. There is also the possibility that a blade element model used in conjunction with the baseline approach could actually produce undesirable handling qualities. Subjective tuning of this type model to correct handling qualities could require extensive adjustment not only to the internal model, but also external interfaces. Further evaluation of using a blade element model for this application should be conducted to more fully assess the impacts.

The AH-64D Longbow Apache application uses models that have been extensively tuned using actual flight data and experienced AH-64D pilots. These models have been used in the engineering simulator for development and experiments. However, the benefits of "dropping in" a high fidelity blade element rotor model may not be fully realized for the same reasons as with the RAH-66 Comanche application.

6. Summary.

The ARWA SS has selected a rotor disk map approach as the baseline approach for modeling the main rotor. The models used are from the aircraft developers and manufacturers. Based on inputs from our SMEs and an evaluation of the TSA/SFA studies and the purpose of the ARWA SS, the rotor disk map approach is sufficient to support the war fighting skills development mission of the current ARWA SS requirements where pilot perception of the position and change of aircraft attitude is of primary importance. The RDM approach offers these advantages: 1) fast and computationally undemanding, 2) choice of selection of best available rotor data, 3) uncomplicated independent variables, 4) accessibility/capability for modification, and 5) flexibility within the simulation model, and 6) simulation of various rotor types. In addition, the selected RDMs will run on the current GFE.

The ARWA SS architecture supports the change to a blade element model approach. It will require additional processing power at higher computing rates. The BEM is of the highest fidelity, and provides the best analytical understanding of the rotor performance. It is not as easy to tune the BEM response for pilot inputs and requests. Table 6.-1 Advantages and Disadvantages summarizes the advantages and disadvantages of the rotor map approach versus a blade element approach.

Implementing the BEM approach and replacing the RDM approach will require some additional tasks and hardware. These tasks include identifying and obtaining existing blade element model source code, documentation, test cases and data, specifying the computational equipment, analyzing and identifying interfaces and connectivity with other segments, modifying and installing the blade element model, testing the blade element model against existing validation data, and revising the documentation, including the

system/segment specification, system requirements specification and the software design document. Table 6.-2 BEM Software Upgrade Estimates summarizes the tasks and estimated hours. In addition, the V&V task becomes greater in the BEM approach than in the RDM approach. It is easier to tweak performance in the RDM where "curve matching" is being accomplished versus "curve creation" in the BEM approach. This is inherent in the analytical versus empirical nature of the BEM approach.

Additional hardware is required to support the implementation of a BEM. The addition of a single VME board with dual processors to the NightHawk chassis for the Sim[illegible] System Module (SSM) will meet the higher computational requirements. The Mo[illegible] MVME-197DP single board computer contains two 88110 processors rated at 153 M[illegible], and 256 MB of memory on the board. Table 6.-3 BEM Hardware Upgrade Estimates summarizes the additional hardware equipment.

Boeing Defense & Space Group, McDonnell Douglas Helicopter Systems, and Illusion Engineering, Inc., contributed to the preparation of this study and to the estimates presented in Table 6.-2 BEM Software Upgrade Estimates and Table 6.-3 BEM Hardware Upgrade Estimates. Additional tasks to modify and upgrade other segments that complement the increased fidelity of a BEM approach have not been analyzed nor estimated

	ADVANTAGES	DISADVANTAGES
ROTOR MAP APPROACH	• Moderate computational speed required • *Already used extensively for real-*time simulation • Dynamic response can be "tweaked" to suit pilot opinion • Uncomplicated independent variables • Accessibility/capability for easy modification • Flexible • Can be modified for various rotor types	• Large amount of precomputing needed to generate rotor maps • Dynamic fidelity inferior to blade-element method • Large effort required to implement engineering data changes
BLADE ELEMENT APPROACH	• Better dynamic fidelity • Direct representation of engineering data • One-to-one correspondence with the best non-real-time engineering simulation • Easy incorporation of unsteady aerodynamics • Straight-forward implementation of blade elastic modes • Easy incorporation of airframe changes • Directly usable for crash investigation • Accurate simulation over the <u>full</u> flight envelope	• Requires very high computational speed and increased hardware costs • Not easy to tailor dynamic response to accommodate pilot-suggested changes

Table 6.-1 Advantages and Disadvantages

TASK	BEM upgrade to RAH-66	BEM upgrade to AH-64D
Define requirements, identify sources and prepare SOWs	500 mhrs	
Evaluate proposals, model performance	200 mhrs	
Evaluate documentation, model test data, model test cases	300 mhrs	
Specify and procure the computational equipment	250 mhrs	
Develop data sampling, plotting, and maintenance tools	1000 mhrs	
Analyze and identify interfaces and connectivity w/other segments	230 mhrs	
Support from model source developer, and data sources	2000 mhrs	
Obtain documentation, test cases and data for specific aircraft rotor system and performance	200 mhrs	200 mhrs
Prepare test procedures for the modified model, including specific aircraft kit performance	1070	
Modify and install the blade element model	450 mhrs	450 mhrs
Perform hardware/software integration	450 mhrs	
Test the blade element model against existing validation data	500 mhrs	500 mhrs
Revise the documentation, including the system/segment specification, system requirements specification and the software design document	250 mhrs	250 mhrs
Impact to V&V effort	Not Estimated	Not Estimated
Upgrades to propulsion, flight controls, and other segments	Not Estimated	Not Estimated
Total estimated manhours to perform Upgrade to a Blade Element Model of the Main Rotor	7400 mhrs to upgrade both ARWA aircraft models [6000 mhrs for initial model + 1400 mhrs for additional model]	

Table 6.-2 BEM Software Upgrade Estimates

Equipment	BEM upgrade to ARWA SS Device 1	BEM upgrade to ARWA SS Device 2
Computing System	Motorola MVME-197DP single board computer with dual 88110 processors, with 256 MB memory. Estimated cost $77,000	Motorola MVME-197DP single board computer with dual 88110 processors, with 256 MB memory. Estimated cost $77,000

Table 6.-3 BEM Hardware Upgrade Estimates

APPENDIX A

The following paragraphs list the acronym and symbols used within this document. They are presented here for reference.

A10.1 Acronyms List

The following acronyms were used within this document.

ADST	Advanced Distributed Simulation Technology
ARWA	Advanced Rotary Wing Aircraft
AVTB	Aviation Test Bed, Ft. Rucker, Alabama
BEM	Blade element model
cg	Center of gravity
CNAV	Coupled navigation
FLYRT	Fly Real Time, a digital aero-model simulation developed by McDonnell Douglas Helicopter Systems
GENRO	Generic Rotor, a digital blade element model used to generate main rotor six-state vector components using set conditions and inputs; used by McDonnell Douglas Helicopter Systems.
GFE	Government furnished equipment
Hz	Hertz
IEI	Illusion Engineering, Incorporated
IFFC	Integrated fire and flight control
MIPS	Millions of instructions per second
MB	Megabytes
NOTAR	No Tail Rotor, an copyrighted anti-torque system without a tail rotor, developed by McDonnell Douglas Helicopter Systems
PVIMS	Pilot-Vehicle Interface Mechanization Specification
RDM	Rotor disk model
rpm	Revolutions per minute
SFA	Selective Fidelity Analysis

SOW	Statement of Work
SS	Simulator System
SSM	Simulator System Module
TRADOC	U.S. Army Training and Doctrine Command, Ft. Monroe, VA
TSA	Task and Skills Analysis
TSM	U.S. Army TRADOC System Managers
V&V	Verification and Validation
VV&A	Verification, Validation, and Accreditation

A10.2 Symbols List

The following symbols were used within this document.

v_i	Rotor induced velocity
A_{1s}	Lateral cyclic control input
B_{1s}	Longitudinal cyclic control input
V	Resultant free stream velocity at the rotor
α_R	Rotor angle of attack
θ_O	Rotor collective blade pitch angle
λ	Inflow ratio
λ_O	Inflow ratio
μ	Rotor tip-speed ratio
μ_O	Rotor tip-speed ratio
ΩR	Rotor tip speed